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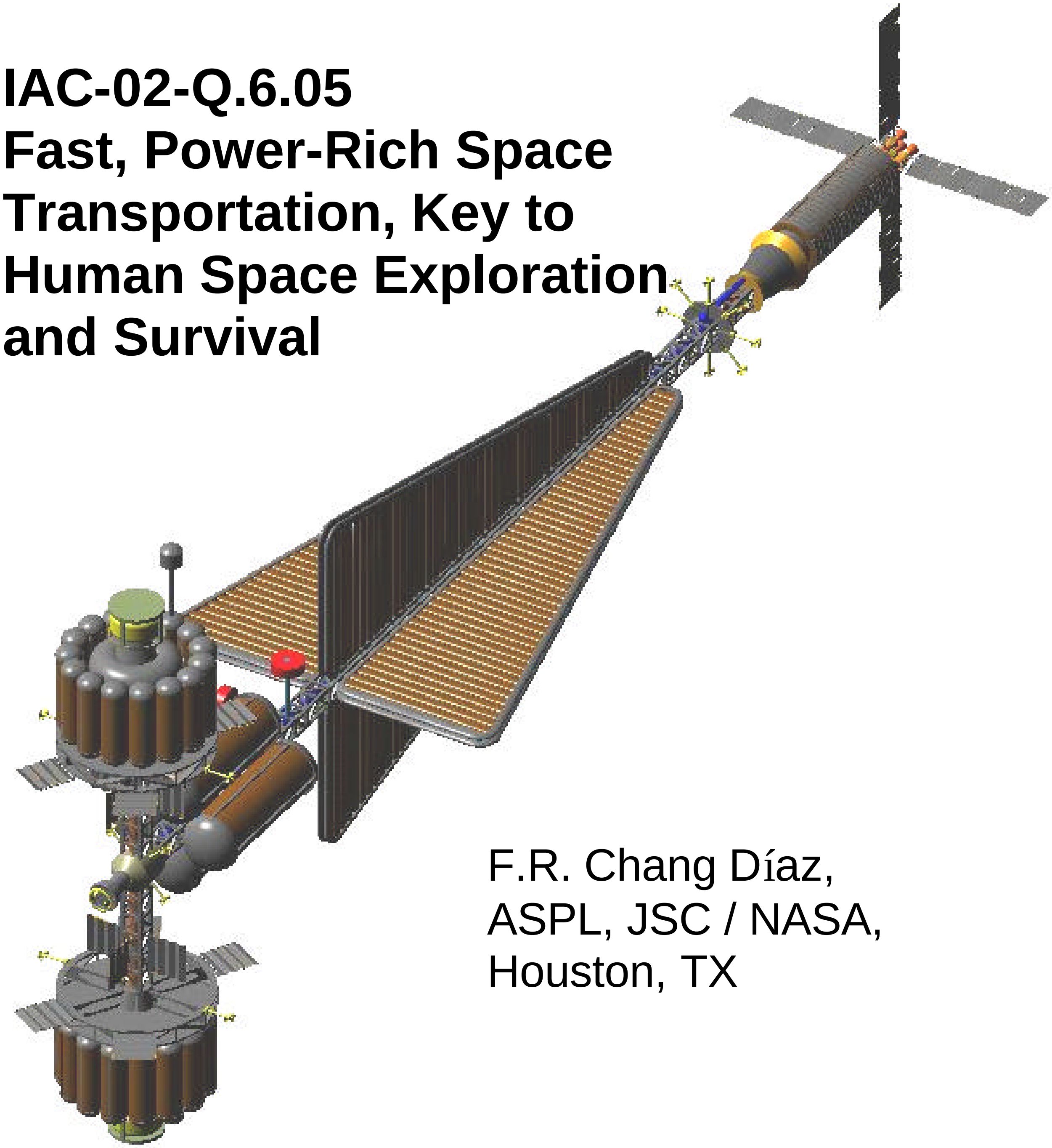
Fast, Power-Rich Space Transportation, Key to Human Space Exploration and Survival



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FAST, POWER-RICH SPACE TRANSPORTATION, KEY TO HUMAN SPACE EXPLORATION AND SURVIVAL

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ABSTRACT

Our future deep space explorers face many daunting challenges but three of these loom high above the rest: physiological debilitation, radiation sickness and psychological stress. Many counter-measures are presently being considered to ameliorate these difficulties; however, in the long run, two important new developments are required: abundant space power and advanced propulsion. Recent initiatives are beginning to focus on these long-term issues. As a result, important technologies currently in the conceptual realm are now being considered for rapid test and deployment. This presentation discusses the promises and the challenges of one of these new approaches, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and the advantages it could have on our capability to survive and explore our new human frontier.

INTRODUCTION

In the summer of 1989, as I prepared to fly on the space shuttle Atlantis, I witnessed a sight I had never seen before in connection with a shuttle launch: demonstrators at the gates of the Kennedy Space Center, calling on NASA to halt the launch. Their cause of concern was Atlantis' payload, the Galileo Spacecraft, slated for a 6-year long journey to the planet Jupiter. Like many of its planetary predecessors, Galileo was powered by two plutonium radioisotope thermoelectric generators (RTGs), which would keep the craft functioning for many years in the depths of space. Fortunately, after unprecedented legal actions, Galileo was cleared to fly. Today, after more than a decade of operations, it continues to rely astounding data and pictures of Jupiter and its moons.

SPACE POWER NEEDS AND RESOURCES

In Space, power is life. Beyond rapid transportation, the power requirements of human space exploration are dictated by our basic biological needs: recycling of our portable environment and utilizing raw materials from the places we visit. On top of this, we will need power to conduct our scientific experiments, to drill deep into the Martian crust in search of past or present life forms, or melt through a thick layer of ice on Jupiter's Europa in search of a potential liquid ocean. Supporting safe and robust exploration requires power-rich spacecraft, with ample margins for astronauts to survive.

Near Earth, the Sun's power has been sufficient for our short human forays into space. However, most experts agree that, while a human Mars mission based on solar power is technically feasible, it is operationally fragile. Beyond Mars, the use of solar power for transporting and supporting human life would not be possible with realistic technology extrapolations. Sunlight at Mars is less than half of that on Earth and at Jupiter it is about one hundredth. As their robotic precursors have done, future human interplanetary spacecraft will rely on nuclear power to explore the far reaches of the solar system and beyond.

Nuclear electricity is obtained from heat produced by the natural radioactive decay of certain radioisotopes, such as plutonium, or the nuclear fission of elements like uranium. In the first case, the electric power is small (tens to hundreds of Watts.) In the second, it can be very large (millions to billions of Watts.) An advantage of fission over radioactive decay is its controllability. Also, since it is based on uranium vis-à-vis plutonium, it is environmentally cleaner. Uranium based fission continues to provide abundant power to ships and cities on Earth. Space reactors have been used to power large spacecraft. Some of these are remnants of the cold war and, while shut down for years, still orbit our planet today.

In space, electricity from fission is best generated with a turbo mechanical heat cycle, using a liquid or a gas as the working fluid. These systems yield a much higher (>30 percent) efficiency than the solid-state devices used in the RTG. A key parameter for gauging the attractiveness of a space power plant is its power-specific mass or "alpha," which refers to the number of kilograms of power plant mass per kW of electrical output. Typical solar arrays (operating

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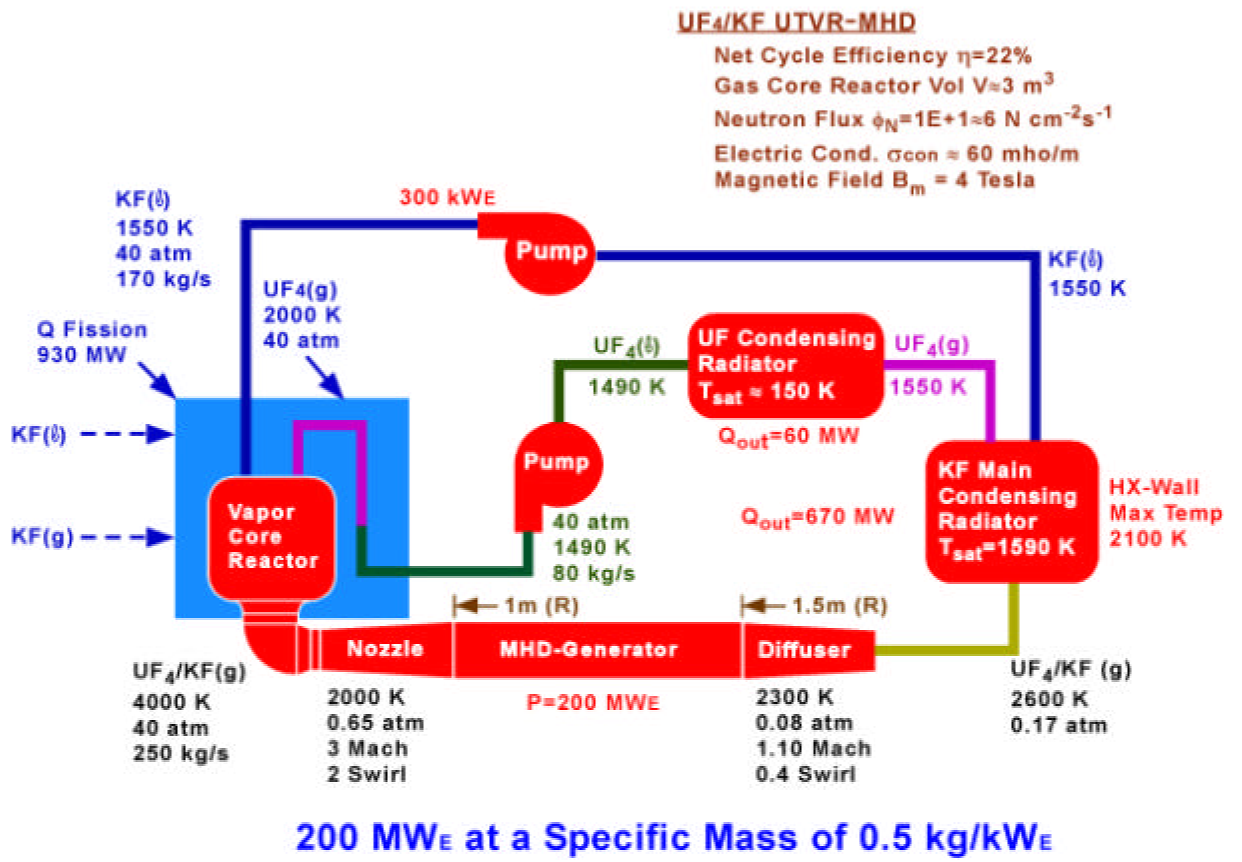

Figure 1: Ultrahigh temperature, vapor core reactor with MHD energy conversion in a closed Rankine cycle. Design by the Innovative Nuclear Space Power and Propulsion Institute of the University of Florida.

near Earth) have alpha values of about 100. Recent studies[1,2] indicate that advanced space reactors can indeed be achieved with alpha values below 1.0. With such systems, a 200-megawatt fission-driven plasma rocket would achieve 39-day transits to Mars. Dr. Samim Anghaie of the University of Florida has designed a conceptual space reactor for this application. This design, shown in Figure 1, is based on a vapor core concept and magnetohydrodynamic power conversion.

Any realistic deployment of this technology must assure the safety of the human population on earth and the crew on-board. The space reactor is launched unfueled and presents no nuclear hazard to planet Earth. The fuel is launched separately, in a configuration where no accidental fission chain reaction is possible. The fueling takes place in a high orbit, where the worst possible accident after reactor-start presents no credible radiation hazard to the planet. Since ascent and descent to the planetary surface is accomplished with conventional rockets, the reactor is kept clear of both the origin and destination planets. At the end of its useful life, the nuclear system can be sent to the Sun or out of the solar system for final disposal.

PROPULSION TECHNOLOGY

Several new and promising concepts are being investigated to provide fast space transportation. Many explore the intrinsic gains in performance afforded by plasma-based systems over their chemical counterparts. Advanced concepts such as VASIMR, Pulsed Inductive and Hall Effect Thrusters, the Gridded Ion Engine, the Lorentz Force Accelerator and others are in various stages of development and field test and offer great promise for the future of space exploration.

Our research group at the Johnson Space Center, is leading a collaborative effort involving government, industry and academia, to develop one of these systems: the Variable Specific Impulse Magnetoplasma Rocket (VASIMR). VASIMR borrows heavily from extensive research in magnetized plasma physics for thermonuclear fusion. As a high-power device, it relies on strong magnetic fields and radio frequency power to achieve a high power density without the need for physical electrodes in contact with the working propellant, a plasma whose extreme temperature would severely damage any material components in close contact with it

Another important feature of VASIMR, beyond its high power architecture, is its capability to modulate thrust and specific impulse to optimize propulsive efficiency. This capability, called constant power throttling (CPT,) is afforded by a number of complementary techniques implemented on several of its system elements. Some of these are briefly discussed below. However, the end result, for very fast trips, is an attractive net gain in payload capability over an equivalent rocket optimized for constant I_{sp}

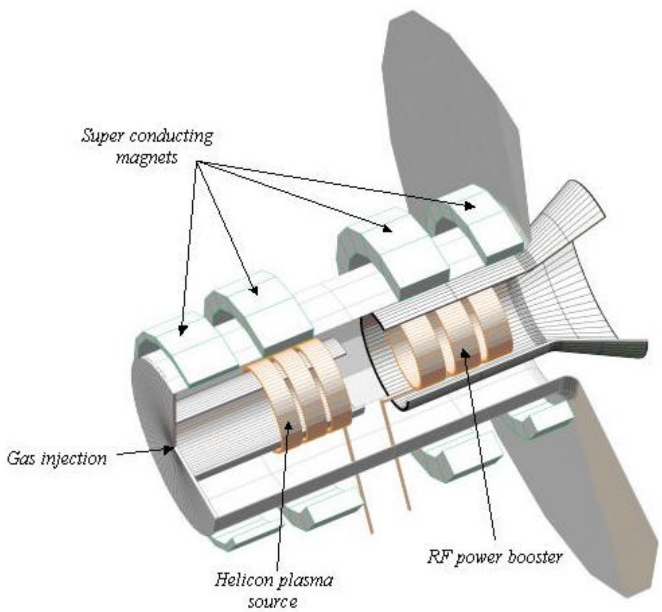

Figure 2: Simplified schematic representation of the VASIMR concept.

THE VASIMR SYSTEM

A very simplified schematic of the VASIMR engine is shown in Figure 2. The device consists of three linked magnetic stages, each with a specific function. Neutral gas (typically hydrogen) is injected at the forward stage and ionized with a device known as a helicon[3]. In it, radio waves ionize the gas in the presence of a magnetic field. The resulting plasma flows along the field to the RF booster, where additional radio waves further energize it. The ions are then exhausted in a magnetic nozzle to provide thrust. The magnetic nozzle converts the cyclotronic motion of the particles into axial velocity. In addition, an ambipolar electric field, generated by the electrons, is also established and contributes to the acceleration of the ions.

With the proper adjustment of the propellant flow in VASIMR, the selective partitioning of the RF power to the helicon and RF booster respectively can control thrust and specific impulse, thereby enabling exhaust variability. For example, if high thrust is desired, RF power is predominantly fed to the helicon injector, with an appropriate reduction in booster power. Thus more ions are produced but with a lower exhaust velocity. If high specific impulse is required, RF power is predominantly diverted to the booster stage, with concomitant reductions in thrust. The total power remains constant.

Other techniques are also being considered, including the use of propellant mixtures and a magnetic choke at the exhaust stage. If the radio wave power is not absorbed completely by the plasma, the magnetic choke could be used to keep some of the plasma longer within the power amplification section and increase its energy content.

EXPERIMENTAL PROGRAM

At the present time, the VX-10 experimental device, shown in Figure 3, at the NASA Johnson Space Center in Houston is exploring the physics and engineering of the VASIMR. Similar experiments at the University of Texas at Austin and the Oak Ridge National Laboratory support this research in a collaborative effort involving 7 universities, private industry and two national laboratories.

Plasma production by the helicon source is efficient. Plasma densities in the 10^{18} to 10^{19} /m^3 on helium, hydrogen, deuterium, nitrogen, argon and other laboratory gases are now routine. The plasma density scales linearly with input power, as shown in Figure 4, with no sign of saturation. The asymmetric geometry of the magnetic field and the ambipolar potential, driven by the electron temperature, produces a rapid plasma flow. Recent data on flow velocity shows that the source alone can deliver an appreciable acceleration to the plasma. This is shown in Figure 5.

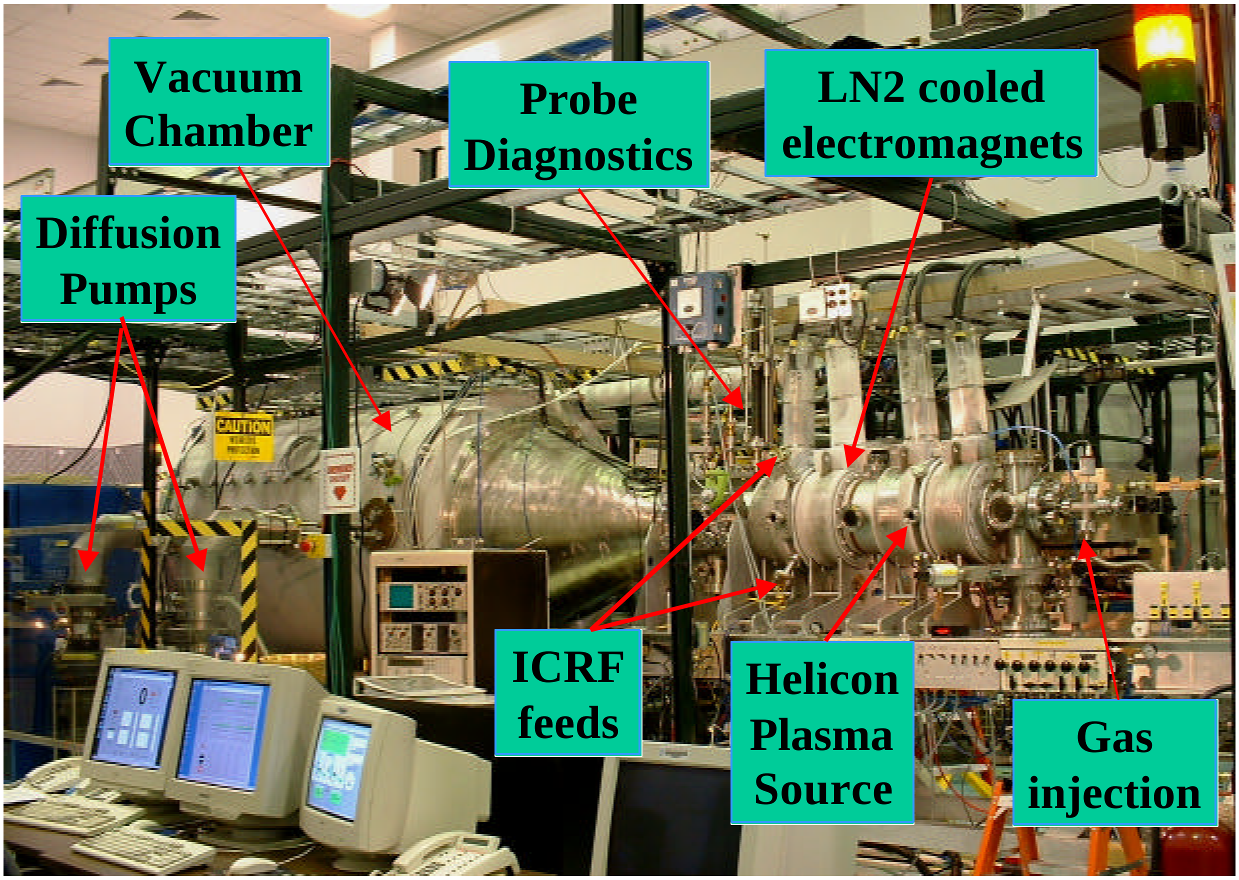

Figure 3: Recent photograph of the VX-10 VASIMR experiment at the Johnson Space Center.

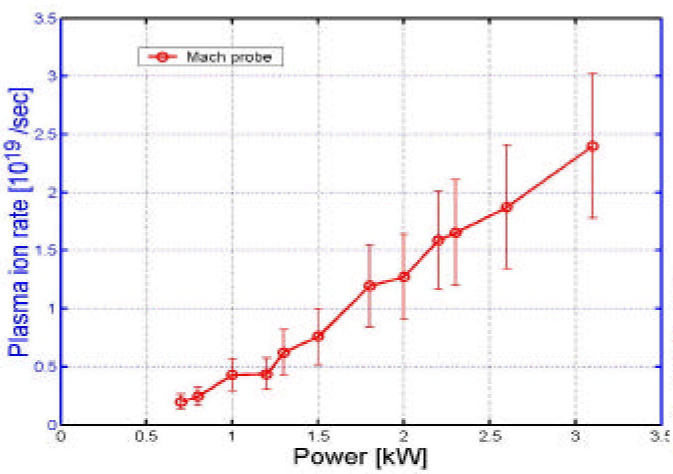

Figure 4: Helicon plasma output vs. power input

A large pressure increase in the helicon chamber is also measured [4] during plasma operation, as well as a commensurate downstream force. These results point to the importance of the neutral particles in providing useful thrust. These particles are ions accelerated by the ambipolar electric field and undergoing neutralization by the charge exchange reaction in the helicon source.

The RF booster stage, currently under development is targeted to operate at the ion cyclotron resonance frequency, but some manipulation of the magnetic field in the system can also enable experiments at the ion cyclotron 2nd harmonic.

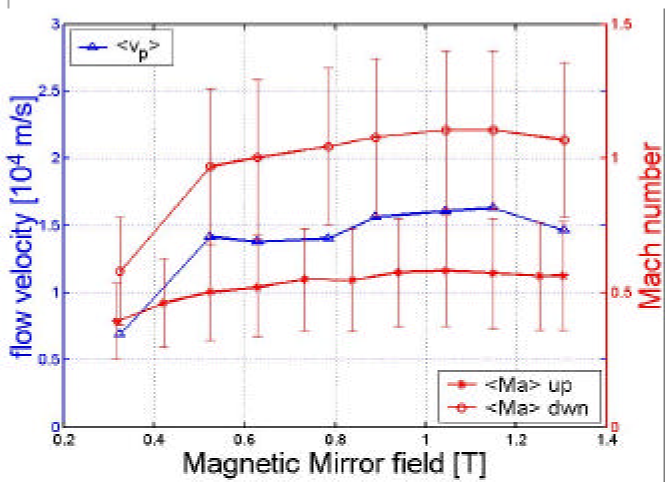

Figure 5: Plasma flow velocity and Mach number for helium at 3kW. Measurements are shown downstream of the magnetic throat.

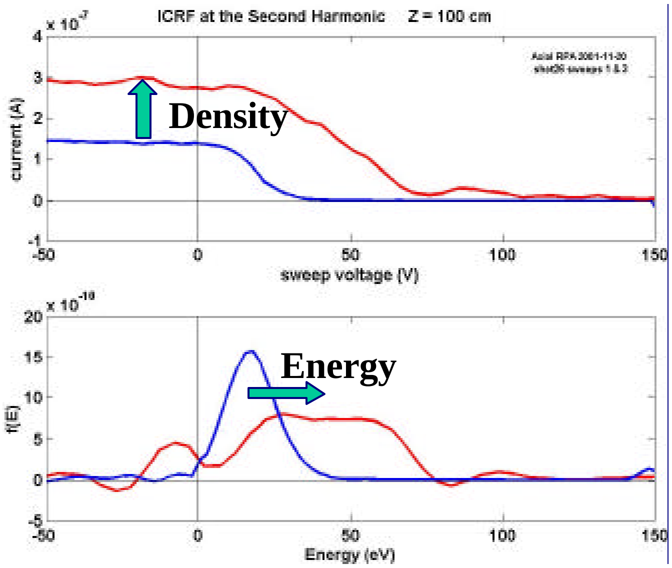

Figure 6: Ion energy data with RF power applied at the 2nd ion cyclotron resonance. Both increases in plasma density and particle energy are observed.

While preliminary, interesting and somewhat surprising results have emerged in recent tests with the RF booster. For example, as shown in Figure 6, the coupling of RF power at the second harmonic resonance, is significant. This result has stimulated thinking on other mechanisms, such as ion Bernstein modes, in addition to ion cyclotron resonance, which may be also employed for wave coupling in the booster stage.

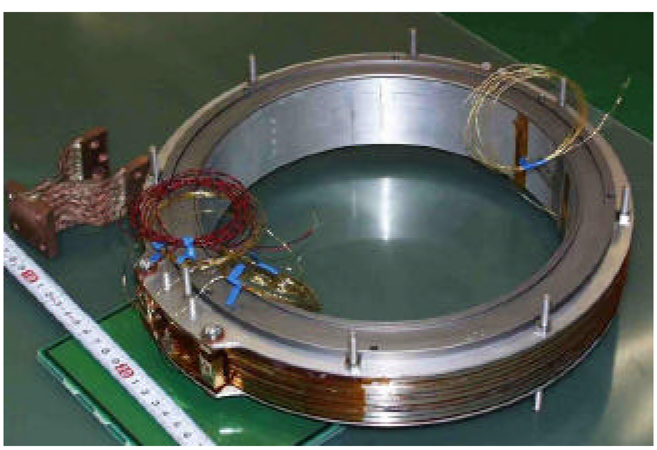

Figure 7: Prototype high temperature superconducting magnet for VASIMR flight demonstration.

ENGINEERING STUDIES

The bulk of the present research is geared to an early space demonstration. To this end, focused studies in superconducting magnets, advanced materials and integrated solid-state RF technology are being conducted. A high temperature superconducting magnet prototype, shown in Figure 7, has been developed and is now undergoing laboratory testing. This magnet has reduced the weight of this subsystem by a factor of 30.

While the RF systems under study today focus on solid-state technology, the requirements for a high power engine will be geared to vacuum tubes. Our research team is currently developing these designs in collaboration with the Oak Ridge and Los Alamos National Laboratories.

Space testing of the VASIMR engine could be carried out on board the International Space Station (ISS). This new orbiting laboratory is quickly becoming accessible to investigators in a variety of fields. As an external attached payload, the experiment would benefit from an unlimited high vacuum capability. Further, the conspicuous effects of vacuum chamber walls, introduced by Earth laboratories would be eliminated.

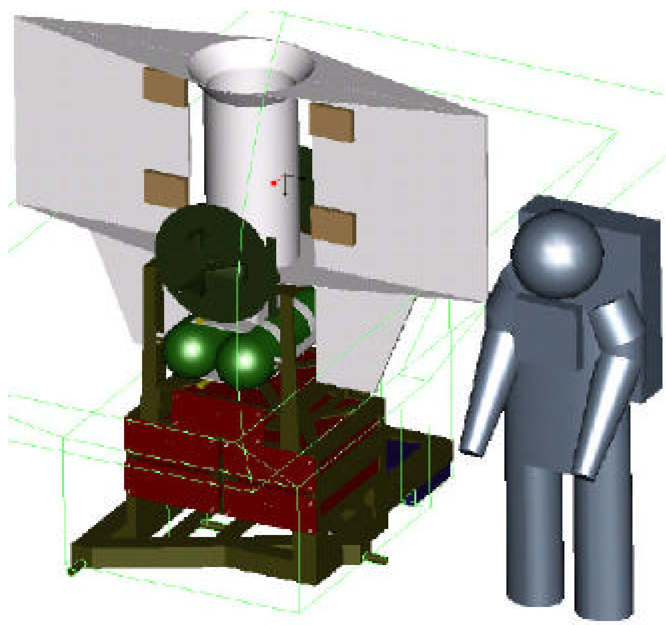

Figure 8: The VF-25 ISS space test article.

Based on the common infrastructure requirements of most electric propulsion devices, we are proposing the construction of a generic electric propulsion test platform for the ISS, which would enable side by side testing and validation of different technologies. At the right location, it could also provide atmospheric drag compensation for the station, greatly reducing re-boost costs. By compensating for drag forces, the continuous thrust of an electric rocket would also provide a true "zero-g" environment, of great interest to other areas of on board research.

A preliminary design for an 1128 Kg VASIMR ISS test article is shown in Figure 8. In order to reduce dependence on ISS power, the system operates on high capacity batteries (60% of the system mass), at 25kW in a quasi-steady state. Thrust and specific impulse are .5N and 5400 sec. respectively.

MISSION STUDIES

A representative 12MW, nuclear-electric VASIMR piloted mission to Mars has been designed with the characteristics shown in Figures 9a-c. The total delivered payload mass is 60 metric tons. Other studies at higher power levels and to other destinations are currently under way. In addition, a comparison of variable vs. constant I_{sp} propulsion is also being carried out as part of an ongoing collaboration with the University of Texas at Austin.

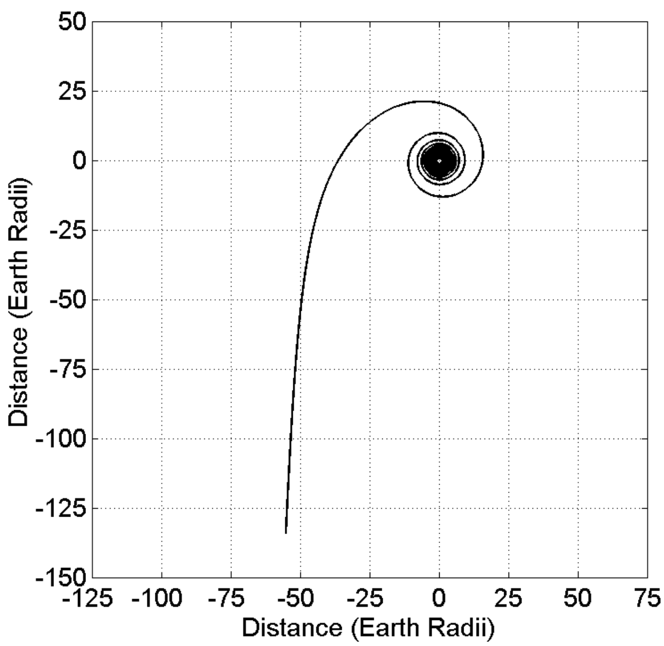

Figure 9a: Initial high thrust Earth spiral (30days)

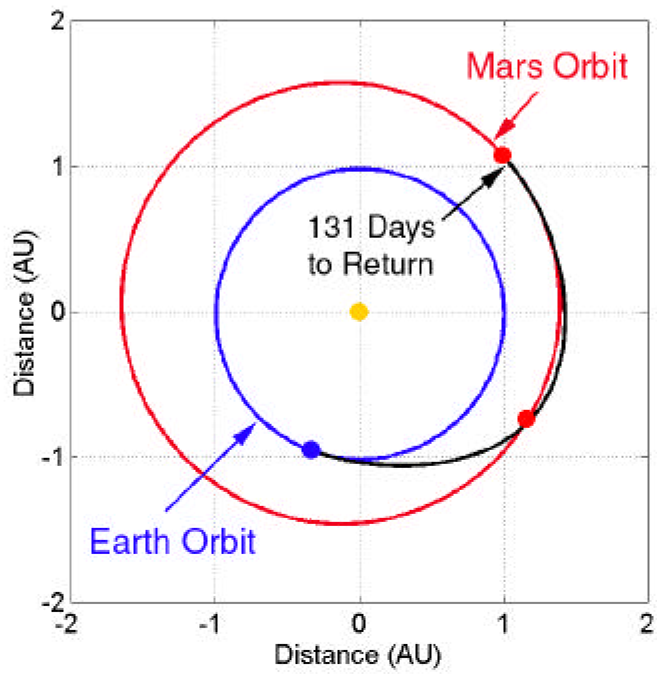

Figure 9b: Heliocentric Trajectory (85days)

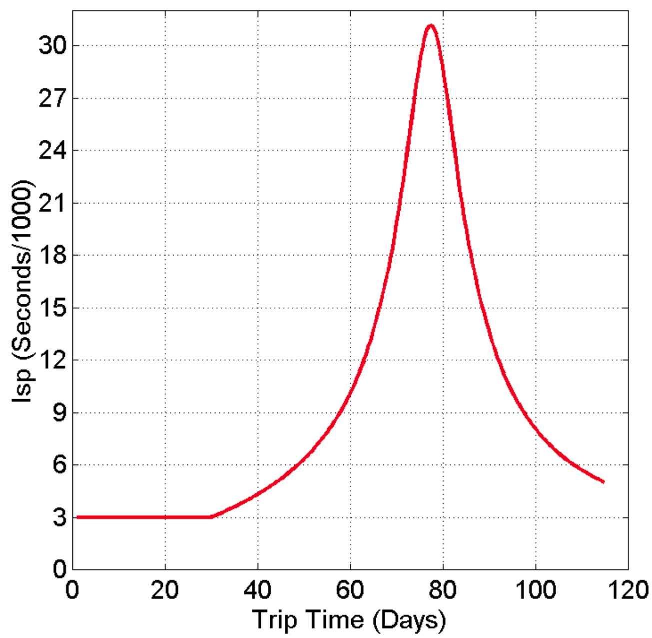

Figure 9c: Specific impulse profile for piloted segment

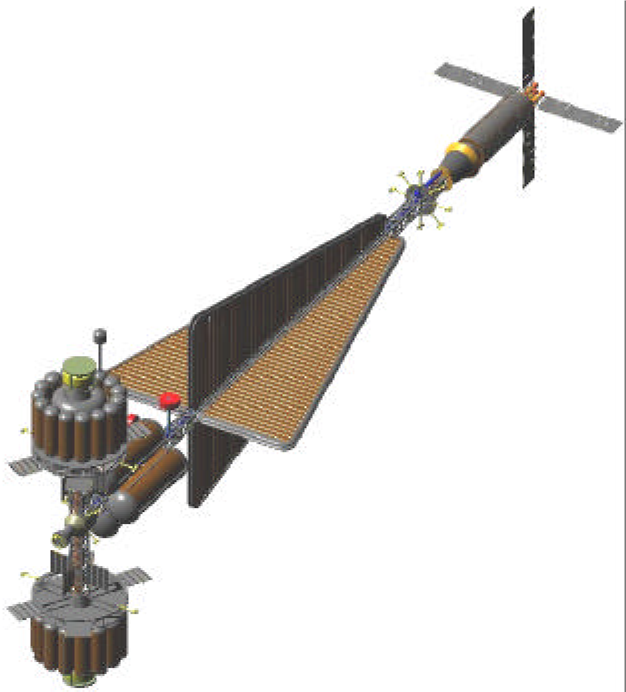

Figure 10: Conceptual design of a 10MW ship for a mission to Jupiter's moon Callisto.

OTHER ONGOING STUDIES

While VASIMR experiments continue in the laboratory, conceptual system studies are being carried out as well. For example, a hypothetical VASIMR driven mission to Jupiter's moon Callisto is being developed in collaboration with the NASA Langley Research Center. The mission utilizes a 10 MW reactor system. A conceptual design of the ship's architecture is shown in Figure 10.

Technology development activities follow a brisk roadmap, shown in Figure 11, building up to increasingly higher levels of power. Initial tests in low Earth orbit will utilize solar power to demonstrate the propulsion system components. Transition to nuclear power could be done with deep space robotic demonstrators, which will pave the way to full human mission in the first quarter of this century.

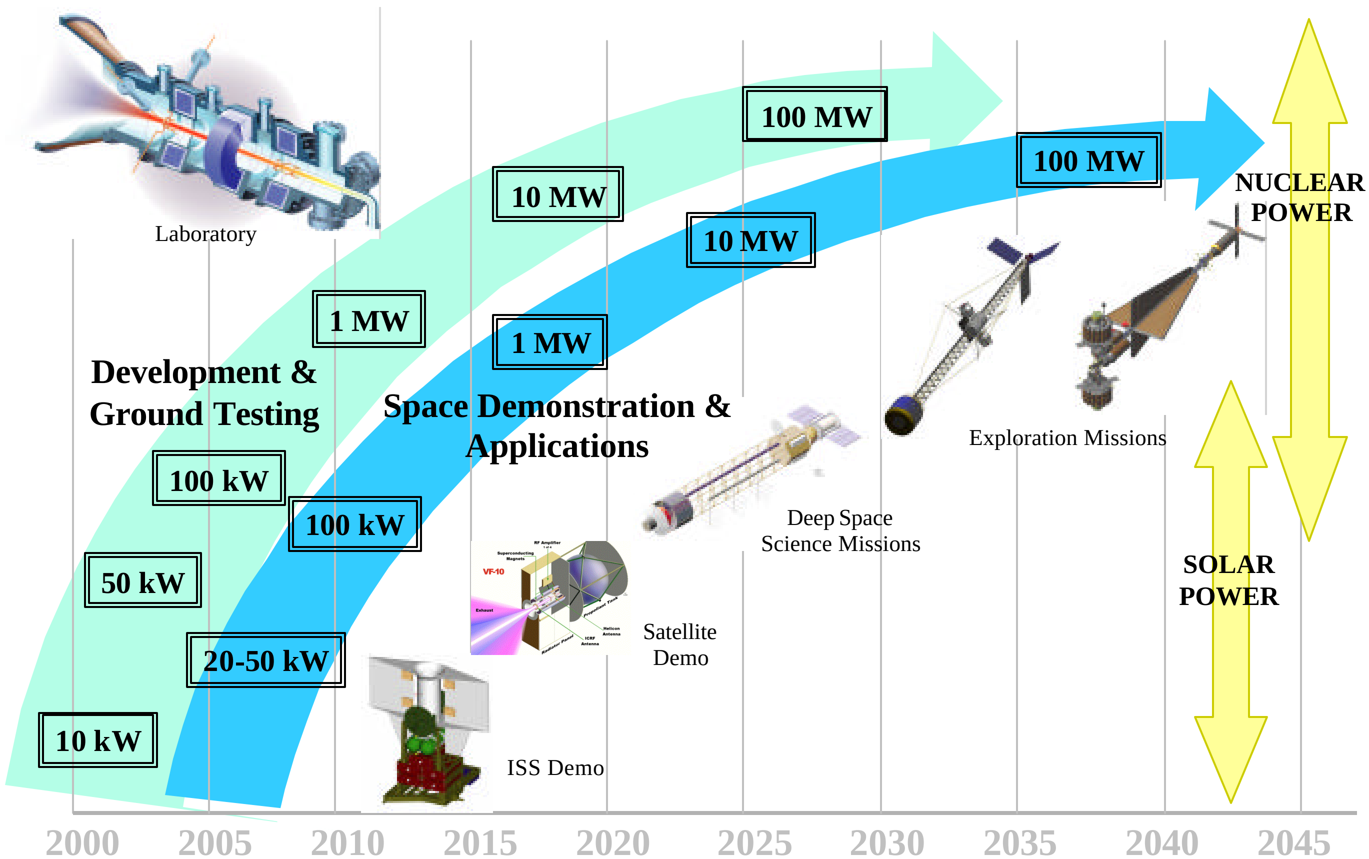

Figure 11: VASIMR Technology Roadmap

CONCLUDING REMARKS

The experimental data continues to provide an exciting outlook. At the present time, the research focus centers on optimizing the helicon source for maximum plasma output. High-density plasma is required to ensure effective coupling to the RF booster. More diagnostics are also being added to the experiment at this time, these are the result of developing research collaborations with the University of Michigan, the Los Alamos National Laboratory and three groups abroad: The Australian National University, The Costa Rican Center for High Technology and the Alfven Laboratory in Sweden.

Safe and reliable electric power, derived from fission, could provide the power-rich architecture needed to sustain human space exploration. Nevertheless, the decision to utilize space reactors must be made by the people of Earth, from an informed and educated perspective. The eventual outcome will have profound implications to our future and must be understood by our young. They will inherit the transparency of our vision.

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